Thermal Operability Improvements for the Mars 2020 Rover Surface Mission

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The Mars 2020 Rover is scheduled to land on Mars on February 18, 2021. One of the primary mission objectives for the Mars 2020 Rover is to perform in-situ science and collect a set of Martian regolith samples for possible future return to Earth. In order to meet mission requirements, 20 samples must be collected, assessed, and sealed during the prime mission (1.5 Martian years, approximately 1000 Sols). This requires that the Mars 2020 Rover operate in a much more efficient and autonomous manner than its predecessor, the Mars Science Laboratory (MSL) Rover, Curiosity. The thermal designs of both Curiosity and the Mars 2020 Rover utilize warmup heaters to bring the actuators and cameras, located on the outside of the vehicle, up to their operating temperatures prior to use. These heaters consume energy during the mission. The Rover energy balance, between energy production and consumption, must be maintained in order to keep the mission moving safely forward. Increased efficiency in the way this warmup heater energy is allocated and used in the Mars 2020 Rover operations plan will result in more energy available for science and engineering activities. This paper discusses the improvements that were made in both hardware and software to improve the way the Mars 2020 Rover will operate thermally on Mars.

Nomenclature

ACA	=	Adaptive Caching Assembly
AFT	=	Allowable Flight Temperature
CacheCam	=	Caching Camera (imager inside SCS)
DTE	=	Direct-to-Earth
EDL	=	Entry, Descent and Landing
FSW	=	Flight Software
GCM	=	General Circulation Model
HazCam	=	Hazard Avoidance Camera
HGA	=	High Gain Antenna
HRS	=	Heat Rejection System

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JPL	=	Jet Propulsion Laboratory
Ls	=	Solar Longitude
LMST	=	Local Mean Solar Time
LTST	=	Local True Solar Time
Mastcam-Z	=	Mast Camera with Zoom feature
MarsWRF	=	Mars Weather Research and Forecasting Model
MMRTG	=	Multi-Mission Radioisotope Thermoelectric Generator
MSL	=	Mars Science Laboratory
NASA	=	National Aeronautics and Space Administration
NavCam	=	Navigation Camera
PRT	=	Platinum Resistance Thermometer
RA	=	Robotic Arm
RAMP	=	Rover Avionics Mounting Panel
RCE	=	Rover Compute Element
RIPA	=	Rover Integrated Pump Assembly
RLGA	=	Rover Low Gain Antenna
RPFA	=	Rover Pyro Firing Assembly
RSM	=	Remote Sensing Mast
RUHF	=	Rover Ultra-High Frequency
SCS	=	Sampling and Caching Subsystem
SuperCam	=	Science Instrument at top of RSM Mast
Sol	=	Day on Mars (duration is 24.66 Earth hours)
Tau	=	Optical Depth of the Atmosphere
TI	=	Ground Thermal Inertia
UHF	=	Ultra High Frequency

I. Introduction

NASA is scheduled to launch the Mars 2020 Rover to Mars in July of 2020. After a seven-month cruise, the Mars 2020 Rover will touch down on the surface of Mars on February 18, 2021. The Mars 2020 Rover will go to a yet-to-be-selected Mars landing site, where it will investigate the geology of the site, assess the habitability of the site and look for signs of ancient Martian life. There are three candidate landing sites remaining: Columbia Hills (at 14.5°S latitude), Jezero (at 18.5°N latitude) and NE Syrtis (at 17.8°N latitude). Final landing site selection will not occur until about one year prior to launch. One of the primary science objectives of this Rover mission is to extract and cache a collection of soil and rock samples from the surface of Mars for possible return to Earth by a future mission. The Mars 2020 Rover design is heavily derived from the MSL Rover design. Many of the changes that were made to the MSL Rover design for Mars 2020 were driven by accommodation of the seven science instruments and the Sampling and Caching Subsystem (SCS). A full description of the Mars 2020 Rover preliminary thermal design, including a description of its science instruments, has been previously published.[1] A later paper describes the detailed surface thermal design of the Mars 2020 Rover.[2]

When the Mars 2020 Rover is fully deployed on Mars, it will have a wheelbase of 2.8 m long and 2.3 m wide, and a ground clearance of more than 60 cm. Engineering hardware, located on the outside of the Rover, is shown in Figure 1. All engineering actuators in the baseline Mars 2020 design are shown in Figure 2. Several papers have been written to describe the MSL and Mars 2020 Rover actuator thermal design modeling and testing efforts.[3-5] There are many heritage hardware elements from MSL that will be re-used on Mars 2020. Some of these are exact copies of MSL designs; others are MSL build-to-print designs with slight modifications. The Mars 2020 mobility system, which has six drive actuators and four steer actuators, will be essentially the same as MSL. The MSL wheels, which sustained significant damage during traverses over sharp rocks inside Gale Crater, have been strengthened (at the cost of increased mass) for Mars 2020. The MSL-heritage Remote Sensing Mast (RSM), which supports the Mastcam-Z and SuperCam science cameras, as well as the engineering Navigation Cameras, stands 2.2 m above the ground. The RSM has three actuators: one azimuth, one elevation and one deploy. There are three external telecommunications antennas, two operating in the X-band (the RLGA and the HGA) and one in the UHF-band (the RUHF). The X-Band HGA has two actuators: one azimuth and one elevation. Direct-to Earth (DTE) communications are done in the X-band and Rover-to-Mars-orbiter communications are done in the UHF-band. The
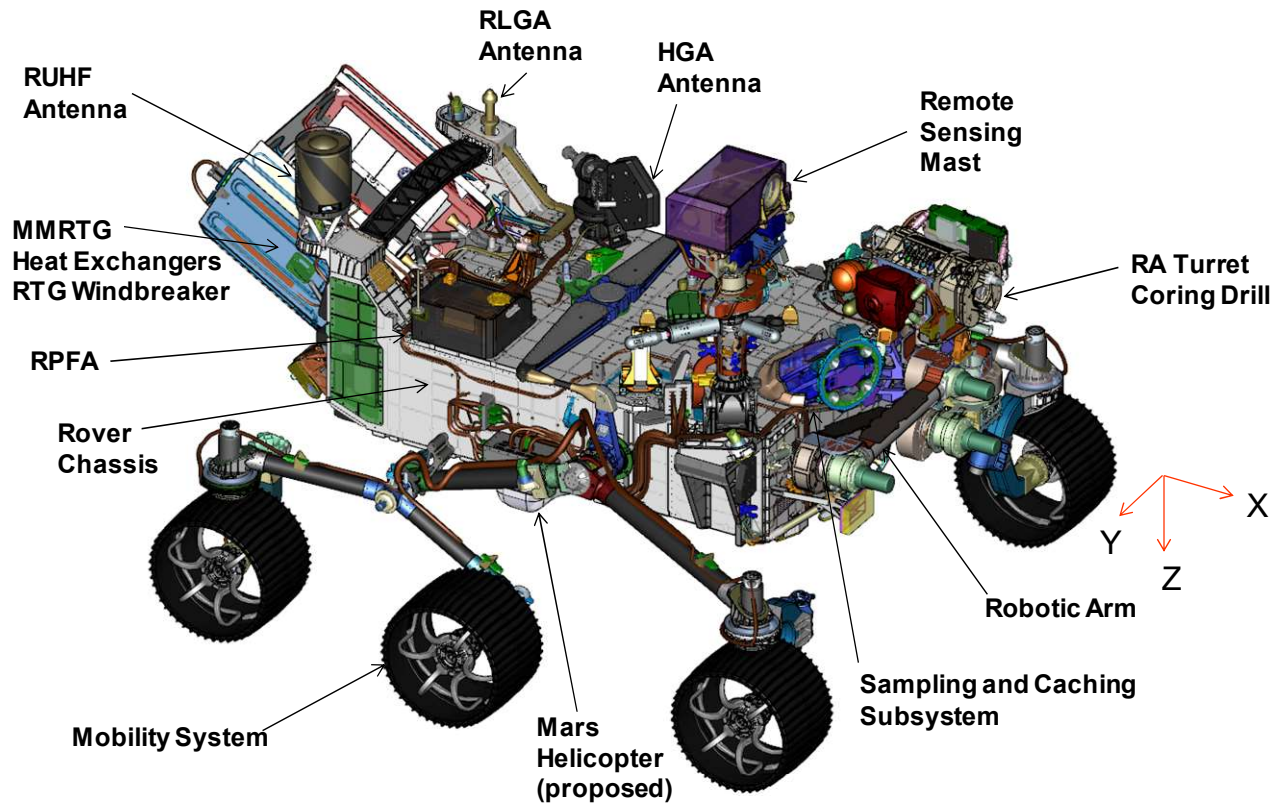
**Figure 1. Mars 2020 Rover and External Hardware.**

MSL-heritage Rover Pyro Firing Assembly (RPFA) is responsible for firing all Rover launch locks and pyro release devices during Entry Descent and Landing (EDL) and after landing. The Mars 2020 Rover is powered by a radioisotope power system, the MMRTG, which dissipates ~2000W of thermal waste heat.

There are many other systems on the Mars 2020 Rover that are completely new designs or extensive modifications of hardware that was previously developed for MSL. The Mars 2020 Sampling and Caching Subsystem (SCS), a completely new design, resides in the front of the Rover and is responsible for collecting and caching Mars rock and soil samples in sealed sample tubes and placing them onto the Mars surface. These sample tubes could be picked up by a future mission and returned to Earth. The largest element of the SCS is a five-degree-of-freedom Robotic Arm (RA). This Mars 2020 RA looks similar to the MSL version, but has new actuators in all five joints. New actuators deliver the fine-pointing accuracy and stability required to operate the new turret-mounted science instruments. The Coring Drill will also be located on the turret, at the working end of the RA. The Coring Drill, having five actuators, will drill into rocks and soil to collect core samples. These core samples will be transferred into the Adaptive Caching Assembly (ACA), located under the Rover top deck, which houses the Bit Carousel (one actuator), a Sample Handling Arm (four actuators) and a Sealing Station (two actuators). All seven of the actuators (motor and gearbox pairs) for SCS will require warm-up heaters to allow operations in cold environments. Figure 2 shows the locations of all 32 actuators on the vehicle. Figure 3 shows the locations of the nine engineering cameras and two science cameras (Mastcam–Z). All of the Rover engineering cameras (two NavCams, six HazCams and one CacheCam) are completely new designs. The NavCams and Mastcams are located on the top of the RSM head. Four HazCams are located on the front of the Rover and two are located on the rear. The CacheCam, used to image samples prior to tube sealing, is located inside the Rover in the ACA.

NASA has asked the project keep open the option of flying a Mars helicopter. The Mars helicopter would be stowed for launch and cruise on the outside of the vehicle under the Belly Pan. The helicopter would be deployed onto the Mars surface, after landing, using a deployment actuator. The helicopter would carry an onboard camera to be used for high-resolution imaging of the potential drive path of the Rover.
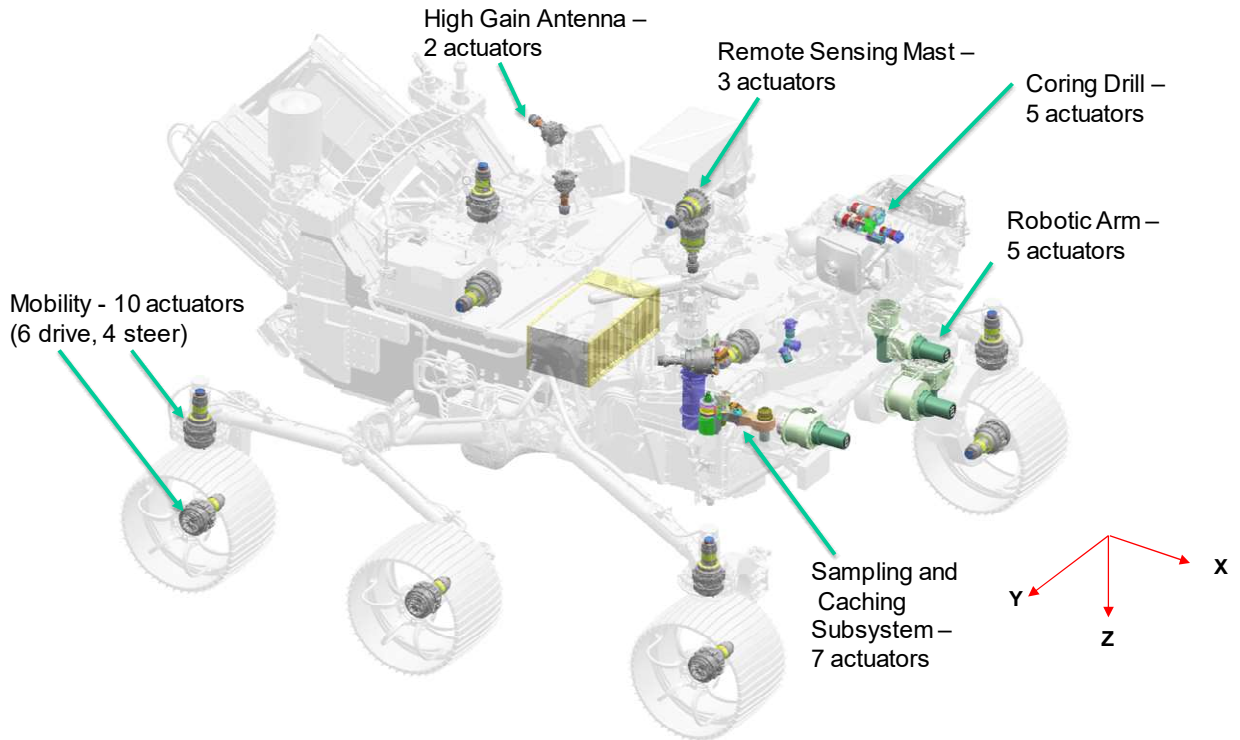
Figure 2. Locations of All 32 Actuators on Mars 2020 Rover.
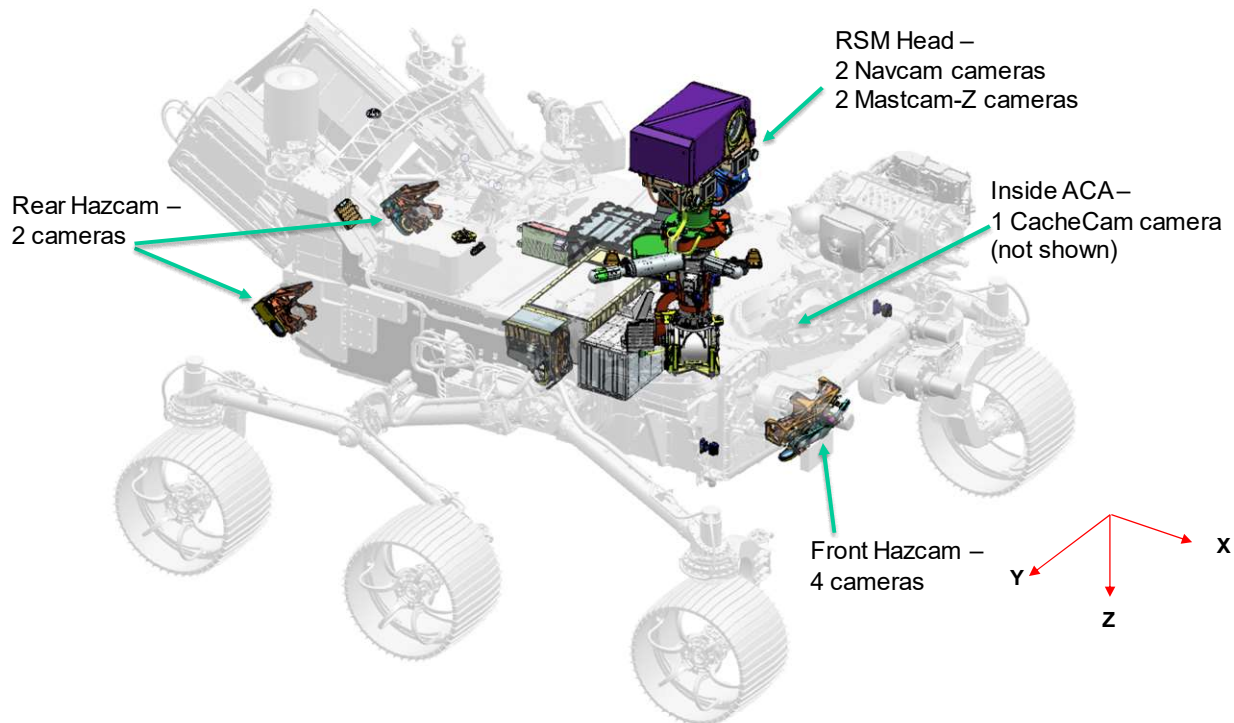
Figure 3. Locations of 11 Cameras on Mars 2020 Rover.

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II. Improving Rover Operability for Mars 2020

The duration of the prime mission for the Mars 2020 Rover is 1.5 Mars years (about 1000 Sols). Over that time period, the Mars 2020 Rover is required to travel 15 km in distance and collect 20 drilled samples. In the first 1.5 Mars years of MSL surface operations, the Curiosity Rover travelled 10.6 km and collected two scooped samples and six drilled samples. The Mars 2020 Rover is being asked to do more science and do it faster than Curiosity. Across the entire Mars 2020 Mission System, there has been a big push to improve operability and efficiency for the Rover.[6-11] The guiding principles for improving Rover operability are:

1) Reduce "ground-in-the loop" cycles by allowing the Rover to make autonomous decisions on its own, without ground intervention.
2) Remove restricted Sols (Sols in which the downlink comes so late in the Earth planning day it results in a one-sol delay) by shortening the tactical time line.
3) Be fast and flexible by performing flight and ground functions more efficiently.
4) Do more science each Sol by reducing the amount of time spent doing engineering functions and increasing the amount of time spent doing science.
5) Make plans easier to build by simplifying and streamlining regular Rover operations.

Each Rover subsystem was asked to outline what steps they could take to improve Rover operability. In the Thermal subsystem, we identified a number of measures that could be taken to improve thermal operability for Mars 2020. The primary focus for thermal operability improvements was reducing conservatism and improving the efficiency of warmup heating needs estimation and resource utilization. The Rover has a finite energy resource dictated by the power output of the MMRTG (about 110W at beginning of the surface mission) and the ability to store energy in its secondary battery. Warmup heating (for 32 actuators and nine engineering cameras that have minimum operating temperature limits of -55°C) uses energy and time that is not directly being used to do science. Reductions in predicted and actual energy usage by warmup heaters will result in more energy and time available to do driving and sample collection.

III. MSL Heating Tables

During surface operations, for both the MSL and Mars 2020 Rover, a Rover plan is formulated at the end of each Sol, to achieve the next day's science goals. The plan is a balance between science goals, available time in the Sol to do science and engineering activities, and available energy in the system to carry out those activities. Part of the time and energy in a plan is allocated to doing camera and actuator warmups. If the predicted time and energy needed to do warmups is not overestimated, there will be more time and energy in the plan to do science activities. The plan is converted into Rover flight software (FSW) commands that can be uploaded to the Rover and executed the next Sol.

On MSL, the method by which warmup-heating predictions from analytical thermal models were translated into uploaded heating commands was through the heating tables. An example of an MSL heating table, produced for the Gale Crater landing site winter season is shown in Figure 4.

SEASON: Winter, Ls90

Table Name:	*Heater_Table_Ls90_2015_0903*																	
Start Use Date:	2015-09-03	Start SOY:	xxx	Start Ls:	1													
End Use Date:	2025-09-04	End SOY:	xxx	End Ls:	150													
User Supplied Sol Number :	400			*Winter Solstice, Ls=90, Sol= 544 – Feb 15, 2014*														
				1st day after fall equinox														
				end of 1st martian year														

Legend:
- Hardware Too Cold (Soak)
- Operable, but not yet analyzed
- No-Heat op window (AFT+5C)
- No Preheat
- No Maintenance
- Maintenance setpoint optimized
- By extrapolation

Heater System	Quantity																
MOB_L&R_Drive																	
	L T S T :	8:22	8:23	9:00	10:00	11:00	12:00	12:55	13:00	14:00	14:42	15:00	16:00	17:00	17:50	17:51	17:52
	L M S T :	8:46	8:47	9:24	10:24	11:24	12:24	13:19	13:24	14:24	15:06	15:24	16:24	17:24	18:14	18:15	18:16
PRT: THRM-2545 (THRM-T-A	Preheat Duration (minutes)		124.1	115.8	94.7	76.3	62.3	46.1	44.5	23.2	0.0	0.0	0.0	0.0	0.0	0.0	
PRT: THRM-2675 (THRM-T-A	Margined Preheat Duration (minutes)		124.1	115.8	94.7	76.3	62.3	46.1	44.5	23.2							
PRT: THRM-2611 (THRM-T-A	Target Temperature (°C)		17.7	16.5	12.2	8.9	6.6	2.3	1.8	-6.5	-55.0	-55.0	-55.0	-55.0	-55.0	-55.0	
PRT: THRM-2754 (THRM-T-A	Lo Setpoint Temperature (°C)		-55.0	-55.0	-55.0	-55.0	-55.0	-55.0	-55.0	-55.0	-55.0	-55.0	-55.0	-55.0	-55.0	-300.0	
	Hi Setpoint Temperature (°C)		-50.0	-50.0	-50.0	-50.0	-50.0	-50.0	-50.0	-50.0	-50.0	-50.0	-50.0	-50.0	-50.0	-300.0	
	Duty Cycle (%)		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-100.0	

Figure 4. Excerpt of MSL Winter Heating Table for Mobility Drive Actuators.

In order to generate this table of warmup prescriptions, a thermal model of the mobility actuators was run in the cold winter environment for Gale Crater, the MSL landing site. The model was run every hour of the day from 08:22 LTST to 17:50 LTST. Before 08:22 LTST and after 17:50 LTST, the unheated hardware for the mobility actuators (the round-wire harness) is too cold to operate. The key operating parameters that allowed heater commands to be generated and energy estimates to be allocated in the plan are in the bottom half of column 2 in Figure 4. For each hour, there is a predicted preheat duration, a target temperature, high and low set points for flight software-controlled maintenance heating and a duty cycle for the maintenance heating. Target temperatures are set considerably higher than -55°C, because actuator PRTs are located on the outside housing of the actuator, which must be heated well above -55°C in order to drive heat into the internal gearbox bearings and gears. Maintenance setpoints are used to keep the actuator from falling below -55°C after the initial preheat. In the case of the mobility actuator, no maintenance heating is needed, so the maintenance duty cycle was set at 0%.

A plot of Mobility actuator temperatures during an actual heating sequence performed on Sol 511 (L_S = 75 degrees), during the first winter of the Curiosity Rover mission, is shown in Figure 5. This plot clearly shows that prior to the warmup at 10:21 LMST, the rear mobility actuators (PRT channels THRM-2610, THRM-2673 and THRM-2545) were at least 10°C warmer (about -50°C) than the front and mid mobility actuators (PRT channels THRM-2611, THRM-2547, THRM-2675, and THRM-2546) which ranged in temperature from -70°C to -60°C. Mobility heaters on Curiosity were not zoned properly to take advantage of the natural heating that takes place on the rear mobility actuators, due to their proximity to the warm MMRTG. Rear mobility actuators were warmed for a longer period (and consumed more energy) than was necessary for them to reach their minimum operating temperature limits.

Generation of heater tables on MSL was a time-consuming process. It took about six work-months of effort to produce a single heater table for all 24 actuator and camera heater zones. As a result, only three heater tables were produced for use on the MSL mission (one for landing day, Ls = 151 degrees; one for Winter Solstice, Ls = 90 degrees; and one for Fall, Ls = 151 degrees). Each time the operations team had to transition from one table to the next, there was a step change in warmup heating prescriptions. More heating tables and tighter granularity on the effects of changing seasons would have saved energy and improved heating accuracy.
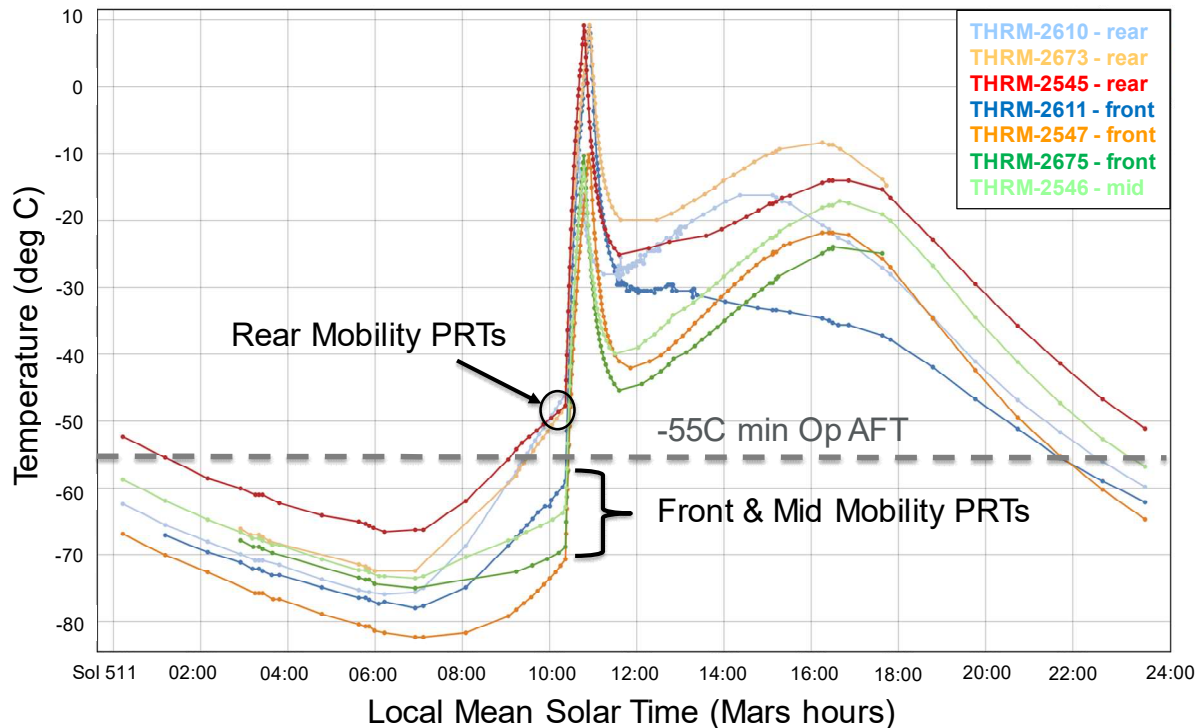
Figure 5. **Temperatures of MSL Mobility Drive & Steer Actuators during Winter Heating Activity on Sol 511.**

Conservative thermal models were used to generate the heating tables, in an effort to ensure that actuators would never be operated below -55°C. Because Rover orientation was not known a-priori, a worst-case orientation (e.g., assuming the actuator was in the shade) was assumed. Heater powers were based on a conservative assumption that the bus voltage was 30V; much of the time during the surface mission, the bus voltage was between 31V and 32V. Because of the conservative model assumptions, the heater tables often overestimated actual warmup time and energy by a factor of two. This was a significant hit to Rover operations from both a planning and an execution standpoint. From a planning perspective, the over-allocation of Rover energy resulted in a reduced amount of planned activity per Sol. From an execution standpoint, the over-allocation of energy resulted in excess unused energy at the end of the Sol. This was clearly not the most efficient way to operate the vehicle.

IV.   Thermal Improvements to Increase Mars 2020 Operability

All of the improvements that were made to the Thermal subsystem, in an effort to increase Rover operability, fall under two of the five guiding principles listed in Section II of this paper. These thermal improvements are in response to:

Guiding Principle #3 - Be fast and flexible by performing flight and ground functions more efficiently, and
Guiding Principle #4 - Do more science by reducing the amount of time spent doing engineering functions.

A. Thermal Improvements in Response to Guiding Principle #3 – Improve Flight and Ground Operations Efficiency

A number of improvements were made to the Mars 2020 Thermal subsystem in order to perform flight and ground functions more efficiently than was done on MSL. The single, most important improvement implemented on Mars 2020 is the use of real-time flight temperature telemetry by the Rover to determine whether warmup heating is needed and if so, how long that warmup heating will take.

There are a large number of variables that affect the temperatures of external Rover hardware. As shown in Figure 6, some of these variables are well known (in green boxes) – Time of day (LTST), Season (L_s) and landing latitude. Many of these variables are uncertain (in yellow boxes) – Tau (optical depth of the atmosphere), ground thermal inertia (TI), ground albedo and local terrain. These variables are inputs to a General Circulation Model (GCM) that is used to generate definitions of Mars thermal environments. The computer model used to generate Mars surface environments for the Mars 2020 mission is known as the MarsWRF GCM.[12-14] Uncertain inputs (in yellow boxes) yield uncertain outputs (also in yellow boxes) that describe the Mars environment – direct solar flux, diffuse solar flux, ground temperature, atmosphere temperature and sky temperature. Other uncertain inputs (in yellow boxes) to thermal models of external Rover hardware include dust coverage on hardware surfaces and Rover bus voltage that dictates heater powers. There are some *very* uncertain input variables (in red boxes) that also influence external hardware temperatures – wind speed, wind direction and Rover orientation. It is precisely these uncertainties, in the thermal model input variables, that drive the large degree of conservatism in the thermal model output (predictions) that was used to develop the MSL heating tables.
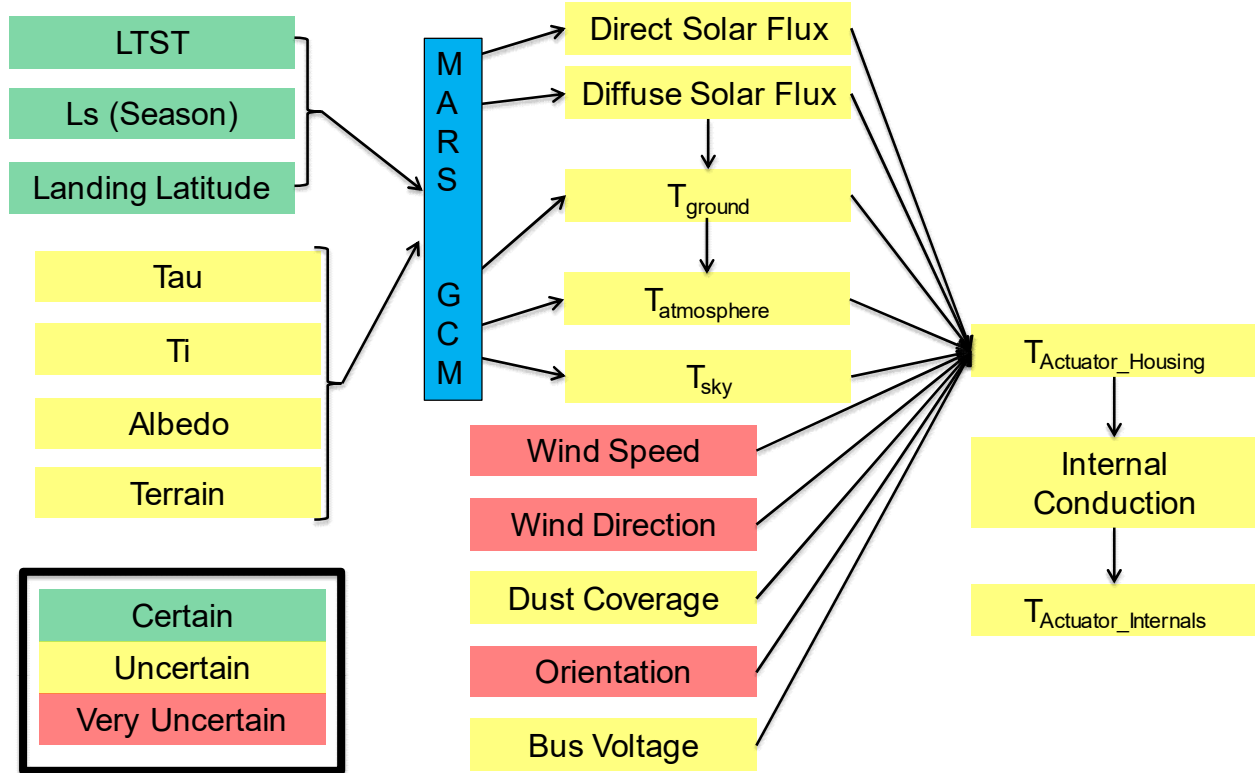
Figure 6. Flow Chart showing Uncertainty of Rover Thermal Model Input Variables Leading to Uncertain Warm-up Heating Predictions.

There were times during MSL operations, when actuators that were already warmed up to operating temperatures by the natural environment or solar loading had warmup commands written for them and executed. Conservative thermal models had predicted colder actuator temperatures than were seen in flight. MSL actuators heaters were turned on and cycled for a specified period of time before the mechanism activity was allowed to proceed. This is an obvious example where, if real-time temperature telemetry were allowed to dictate the heating prescription, no heating would have occurred and the activity could have started right away. Using real-time telemetry to drive actuator warm-up heating can obviously save both time and energy.

Instead of relying on very conservative ground modeling to dictate predetermined and fixed warmup target temperatures and warmup time durations, the plan for Mars 2020 is to allow the Rover to look at the initial temperatures of the actuators immediately prior to heating and use initial temperature-based functions to prescribe target temperatures and warmup times. These initial-temperature-based functions would be resident on the Rover in FSW tables. Using real-time telemetry and heating prescriptions based on a *measured* initial temperature, allows the Rover to eliminate the uncertainties associated with all of the environmental assumptions. It doesn't really matter what interplay of these uncertain variables (shown in the first two columns of Figure 6) resulted in the initial temperature of the actuator housing, all that matters is the value of the initial temperature which is known and read in real-time telemetry by the Rover. Section V of this paper describes how that initial actuator housing temperature will be used to derive heating prescriptions on Mars 2020. Section V also describes how real-time actuator temperature telemetry will be used to assess when an actuator is ready for use and trigger the start of operations. These "event-driven" operations (as opposed to the MSL "time-based" operations) allow more flexibility in the plan, and will result in time and energy savings.

Additional thermal improvements have been made to the Mars 2020 Thermal subsystem in order to allow the system to operate more efficiently. The Robotic Arm actuators now all have PRTs on both the input (motor) and output (gearbox) housings. Having this additional telemetry for thermal model correlation should increase model accuracy (i.e., reduce model conservatism) and improve warmup time duration estimates. Other improvements in ground operations will simplify the translation of heater tables into FSW commands and make the temperature telemetry, whether collected when the Rover is awake or asleep, consistent and accessible in the same database.

B. Thermal Improvements in Response to Guiding Principle #4 – Reduce Time Doing Engineering Functions

A number of improvements were made to the Mars 2020 thermal subsystem in order to reduce the amount of time spent doing engineering functions and increase the time that the vehicle is actively pursuing science on Mars. In an effort to derive a more accurate actuator thermal model and reduce thermal model conservatism, a thermal test of a mobility actuator was performed using thermocouples on internal components of the actuator gearbox.[5] This test improved our knowledge of the internal gas conduction across gear teeth, an effect that had been neglected in MSL actuator thermal models. Through evaluation of the test data, an appropriate modeling technique for gear-tooth gas conduction was derived and used in all Mars 2020 actuator thermal models. This test data has resulted in more accurate and less conservative actuator thermal models for Mars 2020.

On MSL, the actuator thermal models were very detailed, stand-alone models that were never integrated into the Rover system-level model. The thermal models also required working in several different thermal tools and transferring data from one tool to another. These limitations in the thermal modelling process resulted in a very labor-intensive and time-consuming effort (six work-months) to generate MSL heating tables. As a further result, only 3 heating tables were produced for MSL (one used for Spring & Summer, one for Fall and one for Winter). Derivation of more heating tables would have reduced the size of step changes to heating prescriptions when moving from one season to the next and reduced model conservatism. On Mars 2020, all actuator and camera thermal models are being reduced in node count to allow them to be integrated into the Rover system model. The Rover system-level thermal model is running in one tool, so there is no data transfer step between tools. The plan is to automate running of the system-level thermal model so that multiple actuator thermal models can be exercised simultaneously in a number of different Rover seasonal environments (greater than three) to generate more accurate and smoother transitions across seasons. More heater model runs in a shorter period of time will allow more accurate and less conservative warmup prescriptions for Mars 2020.

More PRTs have been added to all mobility actuators and the HGA actuators. These additional PRTs allow the use of "event-driven" heating for these actuators and provide for full visibility into the thermal state of the actuators prior to and during the heating activity. As discussed previously, "event-driven" heating is much more time and energy efficient.

As shown in Figure 5, the rear mobility actuators run at least 10°C warmer than the mid and front mobility actuators. In order to take advantage of this MMRTG heating effect on the rear mobility actuators, the Mars 2020 mobility actuator heaters have been rezoned. The rear actuators now have their own heating switches, independent of the front and mid mobility actuators. This allows staggering of the mobility warmups in recognition that the rear actuators are initially warmer and don't require as much time or energy to get to an operating temperature as the front and mid actuators do. Staggering start times of the mobility actuators will result in less wasted energy.

V. Mars 2020 Heater Table Generation Study - Mobility

In an effort to look at whether the initial temperature of an actuator might be a good way to generate target temperatures and warmup durations, an analytical study was done using an existing mobility actuator model. The study evaluated 36 runs of the mobility model (which has ten mobility actuators) and generated 360 data points to evaluate trends in the predictions. Variables in the runs were:

1. Warm-up start time – 0900, 1200 and 2100 LTST (three variables)
2. Three different Mars environments – specific seasons at 3 different landing sites (three variables)
3. Bus voltage – at 30V and 32.8V (two variables)
4. Wind speeds – at 0 and 15 m/sec (two variables)

Figure 7 shows plots indicating the sensitivity of PRT target temperature (for given PRT initial temperatures) to four different variables: bus voltage, actuator location, wind speed and time of day. Results of these runs show that the only variables that have a significant and consistent effect on PRT target temperature are PRT initial temperature and bus voltage. Note that the environment drives PRT initial temperature. There is a moderate difference between the data points at 30V and 32.8V shown in Figure 7 a). Warmups done at a lower bus voltage (blue data points) have a lower heater power and take a longer time. This longer warm-up time allows the applied heat more time to soak into the internal bearings of the actuator and thus results in a lower needed PRT target temperature. Faster warmups (at higher bus voltages and powers) require a higher target temperature. There is significant scatter in the data points
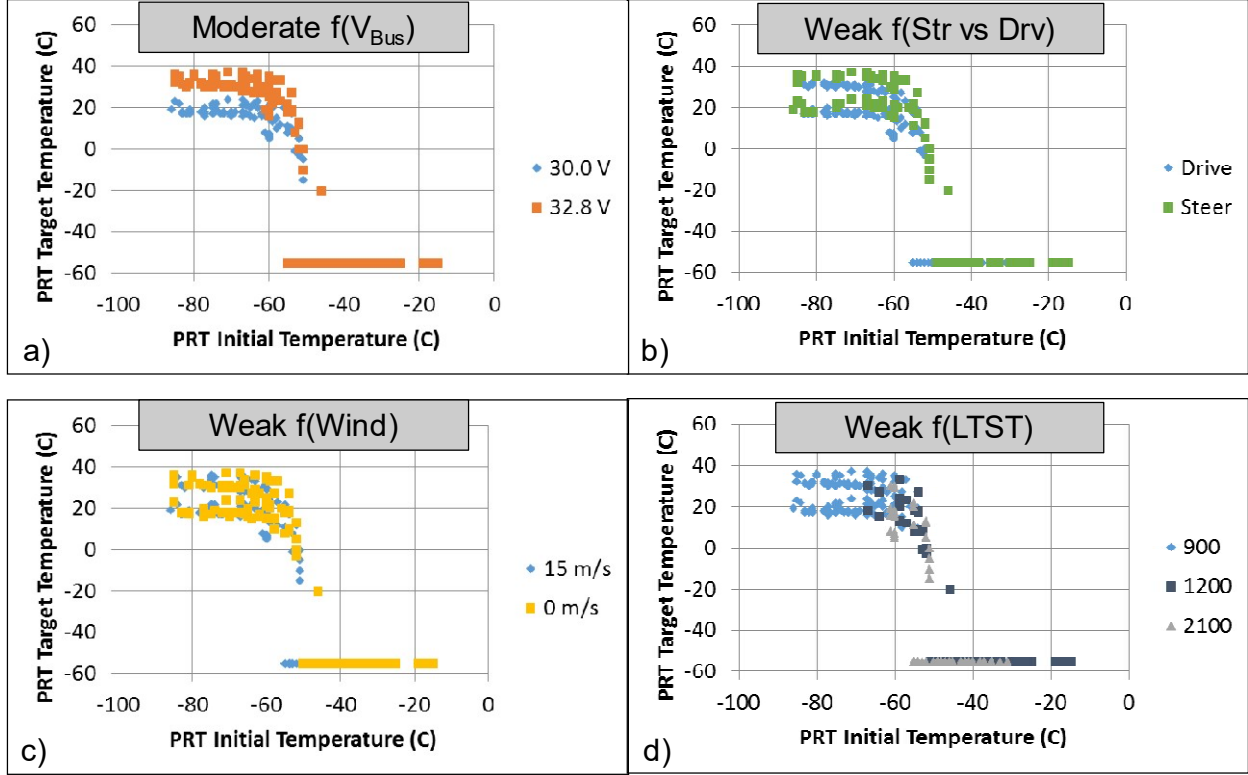
Figure 7. Sensitivity of PRT Target Temperature for given PRT initial Temperatures to each of 4 variables: a) Bus Voltage, b) Actuator Location – Steer or Drive, c) Wind Speed and d) Time of Day (LTST).

shown in Figure 7 b), c) and d), indicating no strong trend. It is appropriate to separate out the effect of bus voltage sensitivity and sufficient to just envelope a bounding curve for the other three variables.

Figure 8 shows plots indicating the sensitivity of warm-up time (for given PRT initial temperatures) to four different variables: bus voltage, actuator location, wind speed and time of day. Results of these runs show that the only variables that have a significant and consistent effect on warm-up time are PRT initial temperature and bus voltage. Note again that the environment drives PRT initial temperature. There is a moderate difference between the data points at 30V and 32.8V shown in Figure 8 a). This is a smaller difference than the one shown in Figure 7 a), for bus voltage versus PRT target temperature, but a definite trend, nonetheless. Warmups done at a lower bus voltage (blue data points) have a lower heater power and take a longer time to warm up. Warmups done at higher bus voltages (and higher powers) have slightly shorter warmup times. There is significant scatter in the data points shown in Figure 8 b), c) and d), indicating no strong trend. It is appropriate to separate out the effect of bus voltage sensitivity and sufficient to just envelope a bounding curve for the other three variables.
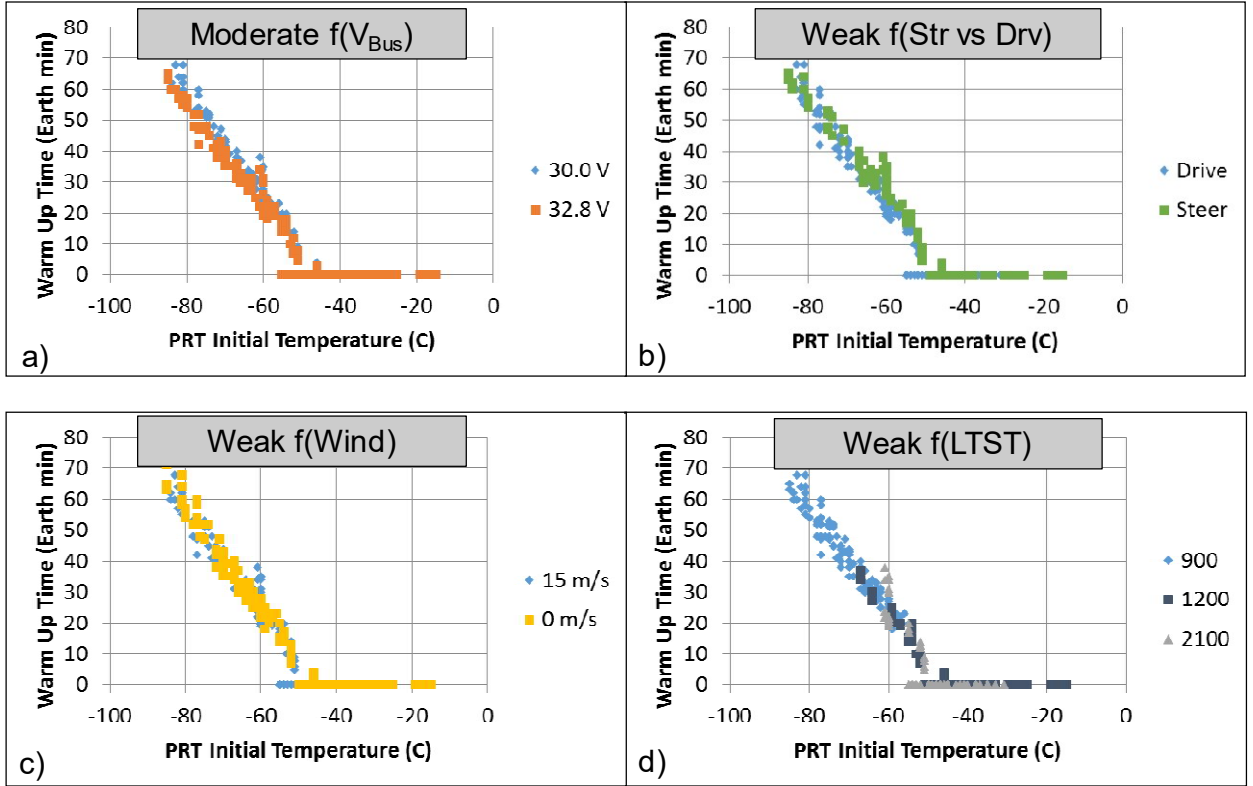
Figure 8. Sensitivity of Warm-up time for given PRT initial Temperatures to each of 4 variables: a) Bus Voltage, b) Actuator Location – Steer or Drive, c) Wind Speed and d) Time of Day (LTST).

Figure 9 shows the notional enveloping curves that will be used on Mars 2020 to dictate the PRT target temperatures and warm-up times for the mobility actuators based on the initial PRT temperatures. These curves will be input to Rover FSW as lookup tables. If the actuator is naturally warmed to an initial temperature ≥ -45C, that indicates no warmup is necessary, and the activity will be cleared to proceed without a heater operation. If the initial temperature is < -45C, then warmup heating is necessary. In order for an actuator to begin operations after an electrical heater warmup, it must both reach its target temperature and wait for the minimum warm up time to elapse since the beginning of warm up heating. The curves in Figure 9 were generated assuming a nominal bus voltage of 30V.

If the actual bus voltage is *higher* than 30V, the target temperature will likely be reached earlier than expected, and the activity start will be delayed, until the specified warm-up time is reached. This ensures that a faster warmup, with higher power, in which the actuator reaches the target temperature *earlier* than expected, will soak long enough to ensure that the internal bearings in the gearbox have been warmed up to operating temperature. In the *higher* bus voltage case, time margin is employed to make sure that the actuator has reached its minimum operating temperature limit.

If the actual bus voltage is *lower* than 30V, it will take longer to reach the target temperature. In this case, the warmup will not be allowed to complete until after the target temperature is reached. In the *lower* bus voltage case, temperature margin is employed to make sure that the actuator has reached its minimum operating temperature limit.
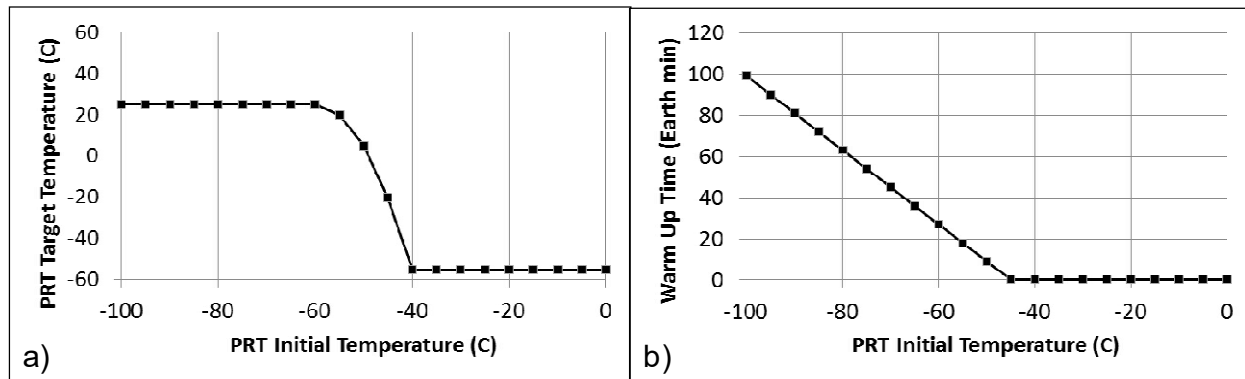
Figure 9. Notional Mars 2020 Actuator Warm-Up Curves: a) PRT target temperature versus PRT initial temperature, b) Warm-up time versus PRT initial temperature

VI. Conclusion

In order to meet its Level 1 science requirements, the Mars 2020 Rover needs significant improvements in Rover operability over the old Curiosity operations model. The Mars 2020 Thermal subsystem has implemented a number of modifications to thermal hardware and software to improve operability. The single, most-important innovation made to improve Mars 2020 thermal operability is the switch from using uncertain thermal models to prescribe warm-up heating (the MSL paradigm) to using real-time flight telemetry, in tandem with thermal model predictions, to drive warm-up heating on the vehicle. Allowing the Rover to select autonomously the appropriate target temperature and heating duration (based on the measured initial temperatures of Rover actuators and cameras) will greatly improve the efficiency of warm-up heating on Mars 2020. Improved efficiencies in the planning and execution of Rover warm-up activities will free up more time and energy for science operations.

Acknowledgments

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